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Properties of Advanced Experimental CMnSiMo Steel Achieved by QP Process

Hauserová, D.[a], Duchek, M.[a], Dlouhý, J.[a], Nový, Z.[a],

[a]*COMTES FHT, Prumyslova 995, Dobrany 33441, Czech Reublic*

Abstract

In relation to technological development in all branches of industry, the requirements for properties of structural materials and for their various combinations are constantly increasing. For instance, the types of advanced materials are sought which would have low procurement costs and high ultimate tensile strength and yield strength while retaining sufficient levels of elongation and toughness. Normally, ductility of materials declines with increasing strength. In some types of steels, special heat treatment can be used to achieve excellent combination of strength, elongation and toughness when compared to conventional treatment processes. One of such advanced heat treatment techniques is the Q-P (Quenching and Partitioning) process. It consists in austenitizing and rapid quenching of the steel between Ms and Mf temperatures to prevent the martensitic transformation from propagating through the entire volume of the workpiece. The subsequent heating causes tempering of martensite and diffusion of excess carbon from martensite to retained austenite, thereby increasing the stability of the austenite. The aim of the QP process is to produce very fine martensite microstructure with retained austenite between martensite plates. The experiment was performed on high-strength low-alloyed steel containing 0.2% carbon and a higher amount of silicon about 1.5%. Higher silicon content contributes to stabilization of retained austenite by suppressing formation of carbides. This grade of steel is a very cost-effective material thanks to its low amount of alloying elements. The entire group of these low-alloyed steels, if heat treated or thermomechanically treated in a suitable manner, offers a favourable combination of strength, elongation and toughness. Thanks to these properties and a low content of alloying elements (i.e. low price), QP steels are used primarily in the automotive industry. The present paper deals with the relationship between parameters of the Q-P process, the austenitizing temperature, the partial quenching temperature and the tempering temperature, mechanical properties and resulting microstructure of the CMnSiMo experimental steel.

Keywords: Q-P process; dilatometer; low-alloyed steel

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1. Introduction

The requirements on mechanical properties of steels are constantly increasing and new heat and thermomechanical treatment processes for such steels are being developed. High-strength low-alloyed steels, as a group of steels, offer favourable proportion of strength, elongation and toughness. The level of ultimate tensile strength required in these materials, upon suitable heat treatment, reaches 1,500 MPa. Their elongation should be around 15%, while the maximum content of alloying and residual elements should not exceed five weight per-cent. Another important requirement consists in good weldability. One of modern heat treatment techniques capable of meeting these requirements is the Q-P process which consists in rapid quenching of a material between the Ms and Mf temperatures in order to prevent full martensitic transformation. Subsequent heating to a temperature below Ms initiates martensite tempering and a diffusion flow of excess carbon from martensite to retained austenite. Cooling down to room temperature stabilizes the retained austenite thanks to prior diffusion of carbon from supersaturated martensite to the still untransformed austenite. The purpose of the Q-P process is to produce very fine martensite with retained austenite between martensite plates. (Fig. 1) [1]. After austenitizing, the steel should be quenched (Q-P) to a specific temperature calculated in such a way as to produce a pre-defined ratio of martensite and non-transformed austenite. Subsequently, the temperature of the material should be raised to the partitioning level (PT). The carbon will diffuse to the existing austenite and increase its stability to the level where it does not transform upon cooling to ambient temperature. As the austenite becomes enriched in carbon during the partitioning stage, its actual Ms-Mf temperatures decrease. Full stabilisation requires that the Ms temperature is depressed to or below room temperature to prevent martensitic or bainitic transformation of insufficiently stabilised austenite during final cooling [2-3].

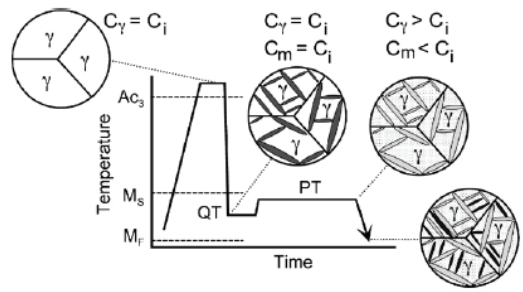

Fig. 1. Schematic Q-P heat treatment [1]

Proposals for new chemical compositions of high-strength steels with the QP effect take into consideration, among other aspects, the requirement for austenite stabilization and cost of alloying additions.

Stabilization of retained austenite in steels is achieved by adding manganese and nickel. Due to lower cost, alloying with manganese is preferred, normally in the amount of 1.5 to 2.5 wt. %. The key to stabilization of retained austenite is also its saturation with carbon during tempering (or during the hold at the partial quenching temperature). The extent of carbon diffusion from martensite to austenite will only be sufficient if cementite is prevented from forming in martensite and at the martensite-austenite boundary. Cementite particles absorb carbon from their surroundings, forming a region of lower concentration, which in turn attracts carbon to diffuse from the surrounding material. This disrupts the desired diffusional flow of carbon from martensite to austenite. Elements which are reported to prevent cementite formation include silicon, aluminium and phosphorus. These elements do not dissolve in cementite and must escape by diffusion from the nucleus if a new cementite particle is to form. This makes cementite formation less favourable in energy terms. The impact of Si, Al and P on formation of transition carbides, such as Fe2,4C, is less obvious. Silicon content normally ranges from 0.3 to 2 wt. %. The amount of aluminium, if used, is no higher than 1.5 wt. %. [4]

Addition of carbide formers, such as Mo, Nb or V, in the cumulative amount of up to 0.3% leads to grain refinement in steel but is very likely to cause precipitation of these carbides in martensite during

tempering [5]. Alloying with these elements is therefore suitable for steels with carbon content of at least 0.2 wt. %. This level should prevent carbon from being used up in forming carbides of these elements during tempering. The precipitated carbides are very fine and are densely and uniformly distributed within martensite laths. This is why they do not inhibit saturation of austenite with carbon as much as Fe3C particles do, where the latter are an order of magnitude coarser. Fine carbides do not absorb carbon from as large an area. They maintain more or less uniform, carbon concentration along the entire martensite lath, though this is lower than in the state without such fine precipitates. The direction of diffusion of carbon from martensite to austenite remains. Fine precipitates also strengthen the martensite matrix of the QP steel.

2. Experimental

Chemical composition of the experimental steel used in this study was proposed to stabilize austenite and suppress cementite formation and in order to support the QP process. However, its alloying included molybdenum for fine-grained microstructure and additional solid solution and precipitation strengthening. Only three additions were proposed: silicon and manganese with 1.5 wt. % levels and molybdenum in the amount of 0.25 wt. %. The carbon content was 0.2 wt. %. As this is the first experimental heat, it appeared useful to keep the chemical composition simple without additional elements, such as aluminium, and thus obtain a reference material for comparing with optimized QP steels with more complex alloying [6]. The initial microstructure consisted of bainite with the hardness of 285 HV30 and mechanical properties as shown in Table 1.

2.1. Heat Treatment

The heat treating operations comprised two processes. The first one was a conventional treatment using an air furnace and water bath, whereas the second one was a physical simulation in dilatometer with an induction heating facility.

Heat Treatment in Furnace and Quenching Device

A series of experimental heat treating Q-P processes was designed. These schedules comprised austenitising at 900°C, partial quenching in water to 250°C and tempering at 350 and 450°C. Austenitising and tempering were carried out in an air furnace. The first two Q-P schedules were intended to explore the impact of tempering temperature on the microstructure and mechanical properties of the material. The other two were aimed at the impact of the partial quenching temperature. The purpose of the conventional heat treating schedule was to provide a comparison of the material's properties with those resulting from the Q-P process. The schedules are detailed in Table 1 and a graphical representation of the Q-P process is given in Fig. 2. The austenitising temperature in all schedules was 900°C and the soaking time was 25 min, which was selected based on 15 mm thickness of the samples. A specially designed mechanism was used for partial quenching in water. It allows to precisely control the dwell time of the specimen in the quenching bath, and thus the partial quenching temperature. Specimens were

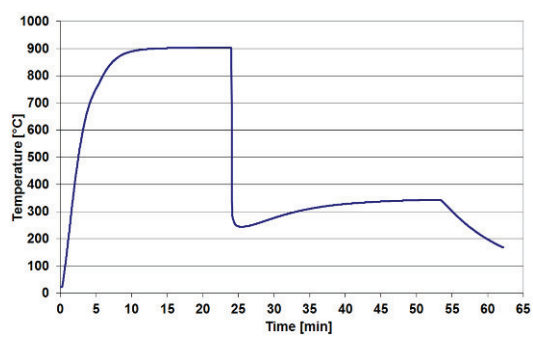

Fig. 2. Heat treatment: Q-P 900/25min-250-350/30min.

tempered at various temperatures in an air furnace for 30 minutes. In the conventional heat treatment process, the tempering step took 2.5 hours.

Metallographic Analysis

The resulting microstructure upon partial quenching in water to the temperature of 250°C and upon subsequent cooling in air (Fig. 3a) consisted primarily of martensite and some bainite. Carbides were present both in and between the bainite plates. The resulting microstructure upon all Q-P schedules consisted of bainite with carbides, tempered martensite and a small amount of retained austenite. These specimens contained considerably more carbide particles than those partially quenched without tempering (Fig. 3b). Some carbides were also found within bainite plates but most carbide particles precipitated between the plates. Martensite laths and bainite plates were relatively fine and uniform in size. Retained austenite was detected by means of standardless quantitative X-ray diffraction phase analysis. Its amount was near lower the detection limit of the method. In Q-P-treated specimens about 3% retained austenite was found. No retained austenite was found in specimens upon conventional heat treatment (Table 1).

The resulting microstructure of Q-P-treated steel is expected to consist of fine martensite and elevated amount of retained austenite without carbides. The presence of carbides is not desirable in this type of microstructure. Metallographic observation revealed that retained austenite stabilisation did not take place to any great extent during tempering. Making the retained austenite more stable requires that martensite–austenite microstructure is obtained. This will be achieved by optimization of quenching and tempering temperatures, which prevent retained austenite decomposition and instead leads to the diffusion of carbon from martensite to austenite. The heat treatment procedure for the experimental material will be further optimised to obtain Q-P microstructure consisting of fine martensite, retained austenite and no carbides.

Mechanical Testing

Specimens for tensile tests had the body diameter of 8 mm and body length of 50 mm. Specimens used for impact testing were of the miniature type, with the size of 3 × 4 × 27 mm and with a 1 mm deep V-notch. Results of the tension test shown in Table 1 indicate that specimens treated according to the first two Q-P schedules, where only the tempering temperatures of 350°C and 300°C were optimized, do not exhibit significant differences between yield and ultimate strength. Elongation values are almost identical in both cases as well. In case of optimisation of the partial quenching temperature, the yield and tensile strength values declined with increasing partial quenching temperature. Upon conventional heat treatment (denoted as HT 900/25min-20-400/150min), the ultimate tensile strength was 130 MPa lower and the yield strength 70 MPa lower than the corresponding strengths in specimens treated according to the Q-P

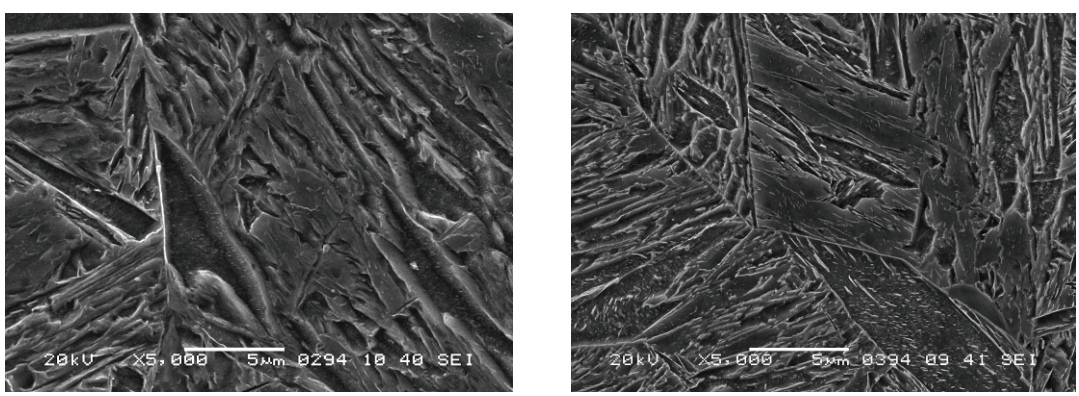

Fig. 3. (a)Martensite-bainite microstructure upon water quenching 900°C/25min-250°C-air.; (b). Bainite with tempered martensite, Q-P 900°C/25min-250°C-300°C/30min.

schedule with partial quenching to 250°C and tempering at 350°C (denoted as Q-P 900/25min-250-350/30min), where the elongation of 15% remained the same.

Table 1 Results of mechanical testing

Schedule	0.2 Proof Stress [MPa]	UTS [MPa]	Hardness HV	A_5 [%]	RA [%]	KCV [J/cm^2]	Retained austenite [%]
Partial quenching 900/25min-250-air	-	-	-	-	-	-	-
Q-P 900/25min-250-350/30min-air	1,176	1,405	438	15.0	64.2	66.4	4
Q-P 900/25min-250-300/30min-air	1,152	1,404	443	14.2	62.1	77.5	3
Q-P 900/25min-270-300/30min-air	1,107	1,382	440	14.6	62.6	80.8	3
Q-P 900/25min-290-300/30min-air	1,099	1,362	435	14.0	63.0	76.7	2
HT 900/25min-20-400/150min-air	1,103	1,272	401	15.2	66.3	63.6	0
Initial state	523	990	285	20.6	44.3	29.1	-

1.1.2 Heat Treatment Simulation in Dilatometer

As the required Q-P-type microstructure was not achieved using a furnace a dilatometer was used for further optimisation. The dilatometer allows the specimen temperature to be precisely controlled with a very short response time during heating and cooling at a rate up to 200°C/s. Furthermore, it records the length change, time and temperature of phase transformations. This physical simulation experiment was conducted using the quenching dilatometer Linseis L78 RITA (Rapid Induction Thermal Analysis), in which the specimens are heated by electrical induction and cooled by a gas flow. Small specimens with the diameter of 5 mm and 10 mm length were used for the above heat treatment schedules. The purpose of the first part of this physical simulation was to copy the Q-P process carried out in the furnace. The second part was aimed at optimizing this process through incremental changes and under conditions which considerably expand the available potential of temperature regulation.

As mentioned above, the core of the Q-P process is partial quenching to a temperature between the martensite start and martensite finish temperatures and subsequent tempering close to the martensite start temperature. For this purpose, the temperature limits of martensitic transformation and the resulting volume fractions of martensite and austenite in the microstructure were determined using the dilatometer. The cooling rates used were 100, 150 and 200°C/s. The martensite start and martensite finish temperatures were found to be 370°C and 220°C, respectively. The volume fractions of martensite and austenite formed in the microstructure are shown in Fig. 4. Regression lines for austenite (pink) and martensite (blue) dilatation were constructed on the dilatometric curve for cooling at 150°C/s. They were used for estimating the dependency of the volume fraction of martensite on temperature during quenching (green curve):

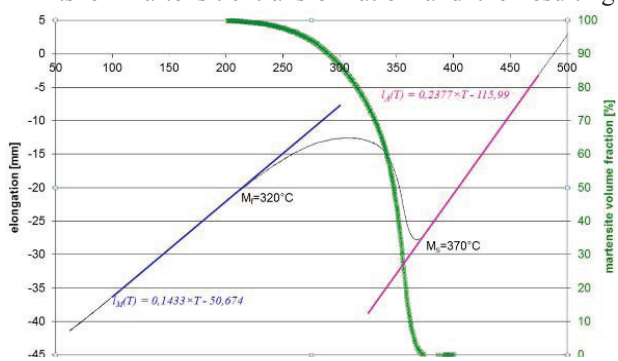

Fig. 4. Dilatometric curve for evaluation of Ms and Mf and the dependency of the volume fraction of martensite on temperature. Cooling rate 150°C/s.

$$l(T) = M(T) \cdot l_M(T) + [1 - M(T)] \cdot l_A(T), \text{ or } M(T) = \frac{l(T) - l_A(T)}{l_M(T) - l_A(T)}$$

where l(T) is the experimentally measured total dilatation, M(T) is the volume fraction of martensite (0-1), $l_M(T)$ is the martensite dilatation, $l_A(T)$ is the austenite dilatation.

The correspondence between the microstructure of specimens Q-P-treated in a furnace and microstructure of those processed in the dilatometer according to the same temperature schedules was verified. Future optimization efforts will be aimed at producing Q-P microstructure consisting of fine martensite with retained austenite between martensite plates.

3. Conclusions

For the present, the Q-P process experiments on the CMnSiMo steel with the carbon content of 0.21% did successfully produce microstructure consisting of tempered martensite and retained austenite without carbides. The resulting microstructure consisted of martensite and bainite with carbides and of up to 4% retained austenite. However, the Q-P process led to certain improvement in some aspects of mechanical properties. The ultimate tensile strength reached 1,400 MPa, which means about 100 MPa increase over that achieved by conventional heat treatment. Elongation measured for all treatment schedules was about 15%. Impact toughness (KCV) values were in the vicinity of 70 J/cm2. A quenching dilatometer was used to make optimization simpler. Martensite start and martensite finish temperatures and volume fractions of austenite and martensite at different quenching temperatures were determined. Metallographic observation revealed corresponding microstructures in specimens treated in furnace and in quenching dilatometer. Q-P process can therefore be optimized more easily by means of a dilatometer and then fine-tuned using large specimens suitable for mechanical testing. This process will undergo further optimization in order to produce the Q-P microstructure: fine martensite with retained austenite and no carbides, and to offer better mechanical properties. It possible to presume that higher stability of retained austenite will be achieved by increasing of both quenching and tempering temperatures.

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